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FINAL FOUNDATION TREATMENT AT HOOVER DAM

By A. Warren Simonds, M. ASCE

SOIL FOUNDATIONS AND FOUNDATIONS DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

FINAL FOUNDATION TREATMENT AT HOOVER DAM

By A. Warren Simonds,[1] M. ASCE

Synopsis

In the design of Hoover Dam, the Bureau of Reclamation (USBR) of the United States Department of the Interior found it necessary to give careful consideration to certain features that were not subject to an exact mathematical analysis. The treatment of the foundation was one of those matters that involved a design based largely on experience and precedent. Because of the height of the structure and the resulting increase in pressure caused by the exceedingly high head, there was no established antecedent that would furnish a suitable comparison for the foundation treatment. However, pressure grouting was anticipated to reduce seepage, to eliminate uplift pressure in the foundation beneath the dam and appurtenant structures, and to correct defects in the bedrock. In addition to the grouting treatment, a drainage system downstream from the grouted area was considered essential. This paper describes the problems encountered in designing the treatment of the foundation, the conditions that developed after the reservoir had filled, and the corrective measures that were undertaken to make foundation conditions agree with the original design assumptions.

Introduction

Hoover Dam is located on the Nevada-Arizona boundary near Las Vegas, Nev., in a deep gorge formed by the Colorado River. The plan of the dam and its appurtenant structures is shown in Fig. 1. It is a concrete-arched gravity structure having a maximum height of 726 ft above the foundation rock, a maximum base thickness of 660 ft, and a crest length of 1,244 ft. The volume of concrete in the dam is 3,251,137 cu yd. Two spillways of the

Note.—Written comments are invited for publication; the last discussion should be submitted by June 1, 1952.

[1] Engr., Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo.

side-channel type, equipped with drum gates, are provided to insure against any possibility of the dam being overtopped by flood discharges. These spillways are located on the abutments a short distance upstream from the dam and discharge into inclined tunnels 50 ft in diameter, driven through the abutments. The power plant is located in the canyon downstream from the dam and consists of 3 sections—the 2 wings housing the power units located on each side of the canyon, and a central section housing the machine shop, dispatcher's room, and offices, situated above the downstream toe of the dam. Water is conveyed to the power units by means of two tunnels (referred to as the upper and lower penstock tunnels) through each abutment.

The canyon in which Hoover Dam is located is known as the Black Canyon of the Colorado River. Before construction excavation was begun, this canyon varied in width from 250 to 500 ft at normal river surface and was from 1,000 to 1,500 ft deep. Excavation of the overburden disclosed that the river had cut a narrow gorge, about 50 ft deep, in the bottom of the canyon.

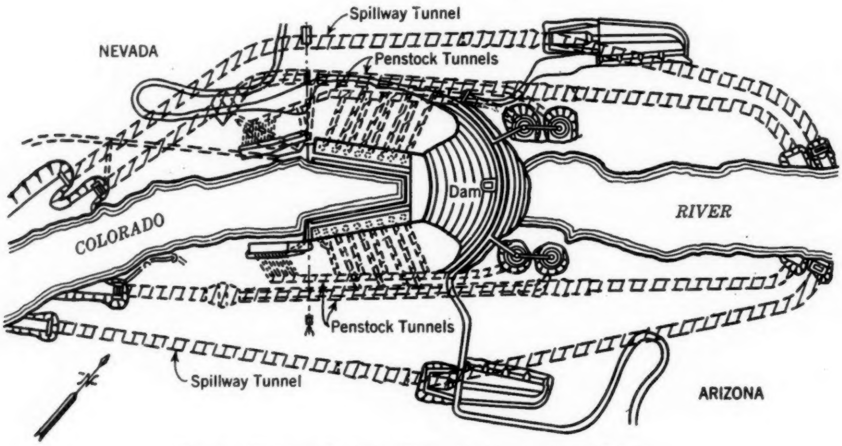

Fig. 1.—Plan of Hoover Dam and Appurtenant Works

On each side of this inner gorge were relatively flat benches at approximate El. 600. The walls of the canyon rose almost vertically to a height of about 450 ft above the benches and then sloped more gradually toward the upper elevations.

The formations at the site of the dam are of volcanic origin. They consist principally of two distinct rocks of different origin and character, both of which are breccias. The lower part of the canyon is cut through an andesitic tuff-breccia that is a dark red, firmly cemented sedimentary breccia. The upper part of the canyon is formed of a light-colored latite flow breccia. The contact between the two breccias is tight and almost indiscernible in places. Although there is an extensive pattern of faulting in the vicinity of the dam, the structure is located on a massive block between 2 well-defined faults. A zone of minor faulting passes through the Nevada abutment, beneath the dam, between El. 840 and El. 940. The formation is characterized by springs of warm alkaline water in the vicinity of the dam.

Sources of Design Information for Foundation Treatment.—Prior to making the actual plans for foundation treatment, an extensive search into the field of pressure grouting was made. Questions involving methods, procedures, grout mixes, and equipment were studied, and laboratory investigations were made to furnish additional information. The principal design problems that were considered were: (*a*) The extent to which the foundation treatment would be necessary; (*b*) the size and spacing of grout holes; (*c*) the location of the cut-off curtain; and (*d*) the location and depth of the drainage curtain.

To aid in solving these problems, a comprehensive study was made of the foundation treatment of 50 of the highest masonry dams. Of this group of dams, those having heights ranging from 300 to 400 ft were selected as the most favorable sources of information on foundation treatment of high dams. This group was comprised of dams that had been constructed by private organizations as well as government agencies.

The investigation revealed that the foundation treatment consisted of forming grout cut-off curtains beneath these dams, extending to maximum depths ranging from 8% to 27% of the height of the structure. In general, the depth of the grout curtain beneath arch dams was less than that of those beneath gravity dams. Beneath massive structures the majority of grout curtains ranged between 15% and 20% of the height of the structure. In addition to the cut-off curtain grouting, the foundation treatment included blanket grouting, the purpose of which was to consolidate a strip of the foundation area near the surface along the upstream side, ranging in width from 5% to 10% of the maximum width of the base.

The holes used for grouting in the dams studied varied considerably in diameter and spacing. The diameters of holes used most commonly were 1½ in. and 2 in., although larger holes up to 6 in. in diameter had been used in some cases. For blanket grouting, the arrangement of grout holes usually consisted of 3 or more rows of holes approximately parallel to the axis of the structure. The spacing of these holes varied from a fairly regular pattern of about 20 ft by 20 ft on centers in each direction to an irregular pattern in which no particular spacing predominated.

The location and arrangement of the grout holes forming the principal cut-off curtains varied considerably beneath the different dams investigated. In many cases the curtains consisted of a single row of holes near the upstream side of the foundation area. In other cases the curtains were formed by two or more rows of staggered holes.

The drainage systems beneath the dams varied from gravel-filled trenches in the foundation rock immediately below the masonry to regular patterns of drainage holes drilled into the bed rock slightly downstream from the grouted cut-off curtain. For the highest dam studied (405 ft), the maximum depth of the drainage holes was 40 ft—about one third the depth of the grout curtain or one tenth the height of the structure.

Original Foundation Treatment at Hoover Dam.—The original foundation treatment consisted of a program of grouting and drainage. In the grouting program three classes of holes were used, designated according to location, depth, and range of pressures. The classes were: A holes that formed the

cut-off curtain and were grouted at high pressure; B holes for blanket grouting that provided a general consolidation of the surface rock and sealed near-surface seams at low pressure; and C holes that were drilled from the upstream edge of the base, inclined in a downstream direction and grouted at intermediate to high pressures. The blanket grouting was done from the surface of the foundation rock prior to placing concrete. The original plans for the C-hole grouting provided for this work to be done after the A-hole grouting and the drilling of the drainage holes had been completed, in order to test the water-tightness of the A- and B-hole grouting and to effect a final seal of the foundation rock. As actually performed, the program was altered to permit commencement of water storage at an early date. The C-hole grouting was begun after 11 alternate A holes at the lowest elevation had been completed, and the grouting of the holes of both series was continued simultaneously, with the

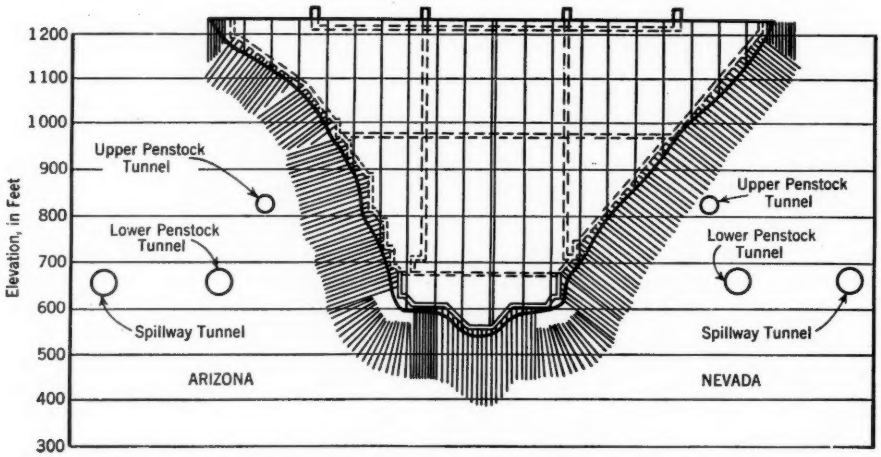

Fig. 2.—Profile of Dam Site Showing Pattern of Original Grout Curtain

provision that A and C holes were not to be grouted on the same side of the canyon at the same time.

When completed, the low-pressure (or blanket) grouting was formed by 5 rows of B holes roughly parallel to the axis of the dam, in the upstream area of the foundation. The holes were spaced at approximately 20-ft centers and had a maximum depth of 50 ft. There was 1 row of C holes drilled from the upstream edge of the dam, spaced at 10-ft centers. These holes were drilled to a maximum depth of 125 ft. The main cutoff curtain was formed by the A holes that were drilled and grouted from a foundation gallery located along the plane of the axis of the dam and immediately above the bed rock.

The A holes forming the curtain grouting were drilled to depths of 150 ft, or about 21% of the height of the dam, across the lower part of the canyon. These holes were spaced at 5-ft centers and the depth of 150 ft was maintained to El. 675. Above this elevation the depth of the holes was decreased uniformly to 100 ft at El. 1200. These holes were inclined 15° upstream from the axis of the dam. The pattern of this series of holes is shown in Fig. 2.

The drainage system was constructed by drilling holes from the foundation gallery. Beneath the lower part of the dam the holes were drilled vertically. At the bottom of each abutment they were fanned (as shown in Fig. 3) until at El. 700 the holes were approximately horizontal. The remaining holes except for the section in the Arizona abutment above El. 1100 were drilled with a slight upward slope so as to drain freely into the gutters of the galleries. The holes varied in depth from a maximum of 102 ft at the lowest part of the canyon to a minimum of 20 ft near El. 1200.

Undesirable Conditions Developed.—During the initial filling of the reservoir, particularly during the years 1937 and 1938, troublesome seepage developed into the penstock tunnels and also through the abutments as a result of the exceedingly high head of water. Water from the foundation drainage system entered the galleries of the dam in excessive quantities in some locations. The uplift pressure on the base of the dam increased to undesirable magnitudes in certain areas, particularly along the Nevade side of the dam and beneath

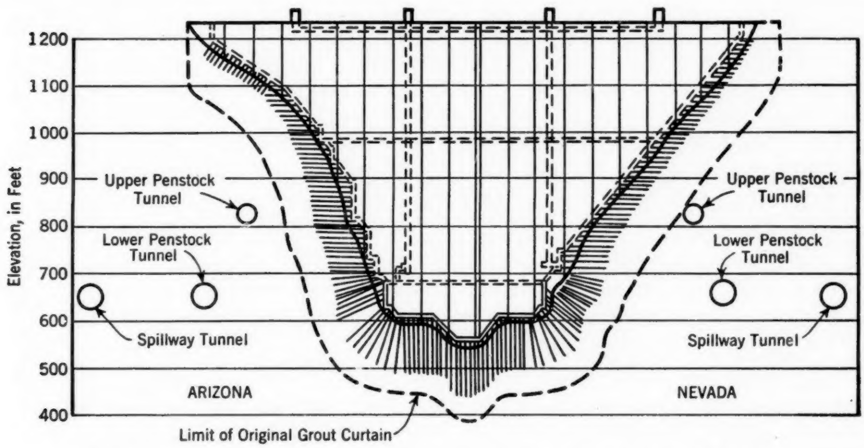

Fig. 3.—Profile of Dam Site Showing Pattern of Original Drainage System

the downstream tow of the dam under the central section of the power plant. These three factors—the seepage, the discharge from the drains, and the high uplift pressure—served as a warning that the foundation conditions beneath the dam were far from satisfactory.

These difficulties were apparently the result of insufficient grouting prior to filling the reservoir. However in planning the original scheme of foundation treatment it was realized that additional grouting would probably be necessary at some future time, so when these undesirable conditions developed they were not altogether unexpected.

Inadequacy of Original Grouting.—In the original grouting program several complications developed that impaired the effectiveness of the desired watertight barrier in the foundation and abutments of the dam. The complications consisted of leaks of grout into the abutment joints (described in the following sections) and difficulties resulting from geologic features of the site. The

first of these factors could be remedied mechanically but the second required study, exploration, and development of equipment and methods.

The mass concrete at Hoover Dam had been placed in blocks that were bounded by radial and circumferential joints, After the concrete had been placed and artifically cooled to a predetermined temperature distribution, the contraction joints between the blocks were grouted to make the structure monolithic. A specially designed joint between the concrete and the rock had been constructed at each abutment. These joints had not been grouted prior to filling the reservoir because it was contemplated that additional tightening of the dam against the abutments would be necessary at some future time, after the structure had deflected downstream under water load.

At the time the A-hole grouting was in progress, grout leaked from some of the holes into the abutment joints. Because of the inaccessability of the leaks it became necessary to abandon the grouting of the leaking holes rather than take the risk of fouling the grouting systems of the abutment joints. This procedure left gaps in the cutoff curtain through which percolation developed. On the Nevada side of the dam the grout curtain was formed by 191 A holes, and of this number 33 holes had been abandoned while grouting was in progress. On the Arizona side of the dam, the grout curtain consisted of 202 A holes of which 21 holes had been abandoned. On the Nevada abutment, between El. 840 and 940, several grout holes had penetrated a fault zone, and 4 grout holes in this area were abandoned, chiefly because of excessive quantities of grout that had been injected into them. Minor leaks had occurred at 3 of these holes.

Contributing Geologic Features.—Several geologic features at the dam site were possible sources of seepage and uplift pressure. Two distinct minor faults crossed the right abutment of the dam between El. 840 and El. 940. These faults apparently were branches of the fault that appeared at about El. 1100 upstream from the dam. When the reservoir water surface reached the faulted area upstream from the dam, the abutment drains in the Nevada abutment began to discharge water. This water was cool, a fact that indicated that the water had its origin in the reservoir rather than in the hot springs that were characteristic of some parts of the foundation area.

During the construction period, when excavation for the dam had been completed in the river channel area, shallow drainage holes were located in the inner gorge of the excavation and along the bench at El. 600 on the Nevada side of the canyon, wherever seepage or shattered zones were found. The flow from these holes (usually warm water) was piped to the drainage gallery at about El. 555. Later, when the dam was practically finished, an attempt was made to grout these holes. The grouting was ineffective due to premature set of the cement, and the pipe headers, to which the holes had been connected, were plugged. Subsequently the flow from the warm springs apparently filled the zones of close shearing beneath the dam, thereby causing excessive uplift pressure to develop. The location of the shear zones is shown in Fig. 4.

Another geologic feature that had caused considerable speculation was the presence of manganese seams in the foundation rock. These seams were known locally as "mud" seams because of the dark color of the drill cuttings

as compared to the normal reddish brown color of the andesitic cuttings. These seams varied in thickness from a fraction of an inch to several inches. Grout holes frequently crossed the seams, particularly along the axis of the dam beneath the galleries at El. 553 and El. 603. Because of the soft nature

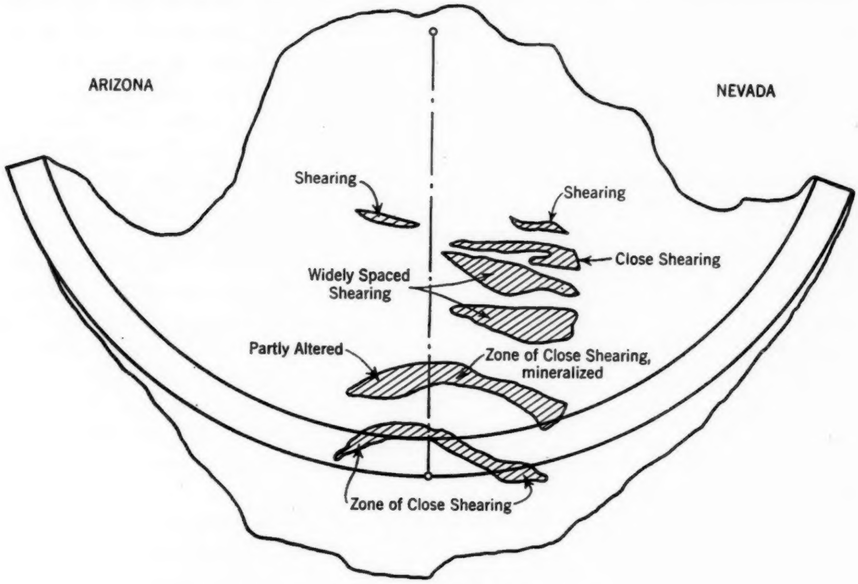

Fig. 4.—Shearing Zones in Foundation

of the manganese in the seams it was difficult to obtain good cores of this material, but one of the better specimens of core showing the manganese seam is shown in Fig. 5.

Purpose of Additional Grouting and Drainage Program.—The purpose of the program of additional grouting and drainage was to correct the undesirable foundation conditions. The specific results that were to be accomplished are as follows:

(*1*) To reduce the uplift pressure acting on the base of the dam, particularly in the area at the downstream toe beneath the central section of the powerhouse;

(*2*) To reduce the seepage through the abutments, especially behind the Nevada and Arizona wings of the powerhouse;

(*3*) To eliminate the seepage of hot alkaline water through the concrete lining of lower Nevada penstock tunnel. This seepage water was injurious to the protective paint of the penstock; and

(*4*) To eliminate seepage of cold water into the upper Nevada penstock tunnel and both Arizona penstock tunnels.

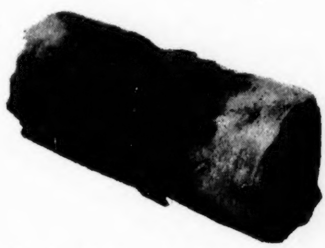

Fig. 5.—Manganese Seam in Core Drilled From Foundation of Hoover Dam

Extent of Foundation Treatment.—The grouting consisted of an additional cutoff curtain with an entirely new and deeper system of A holes. This curtain was formed by utilizing the original drain holes of the dam that were drilled to such depths as the foundation conditions required. The area in the Nevada abutment, beneath the intake towers and the Nevada spillway tunnel, was grouted. The grout curtain was extended into the Nevada abutment from the original A-hole system beneath the dam 600 ft to the right of the Nevada spillway tunnel. The voids behind the concrete lining and the surrounding rock of the lower Nevada penstock tunnel were regrouted, starting at the tunnel plug and extending downstream for a distance of about 300 ft. An area in the Arizona abutment between the left wing of the powerhouse and the Arizona spillway tunnel was also grouted.

An entirely new drainage system was formed by drilling from the grouting-and-drainage gallery into the foundation and abutments downstream from the new system of grout holes. A number of drain holes were drilled beneath the central section of the powerhouse at the downstream toe of the dam, and a series of drain holes was drilled from the Nevada penstock tunnel through the hot spring area in the abutment downstream from the dam, behind the right wing of the powerhouse. A series of drains was also drilled downstream from the grout curtain that extended into the Nevada abutment. This series was drilled from a construction adit extending from the powerhouse to the Nevada spillway tunnel.

This program involved the injection of 251,115 sacks of cement into the foundation and abutments of Hoover Dam under difficult and severe conditions. There was a total of 298,383 linear ft of drilling of which 34,115 ft were for drainage purposes. The remainder was for grouting and included the drilling of additional grout holes, redrilling of hardened grout from holes for deeper stages, reaming holes, and miscellaneous drilling necessary for the grouting program.

Conditions Necessitating Additional Grouting

The conditions that developed at Hoover Dam, as the reservoir filled, were far from ideal. The initial filling was accompanied by the appearance of seepage in prominent places at the dam site. A wet area developed at a conspicuous place on the Nevada canyon wall above the powerhouse roof, at about El. 800. The flow was not great, but it presented an unsightly appearance because of its location. The most troublesome seepage developed in the lower elevations of the canyon, behind the wings of the powerhouse and in the areas adjacent to the 50-ft diameter tunnels. The seepage behind the powerhouse increased until it became necessary to excavate small trenches in the floors of the lower galleries of the powerhouse to serve as drains for the accumulated water.

Seepage into the penstock tunnels was another undesirable condition. The concrete in the arches of the tunnel lining had been placed by pneumatic methods and the quality of this concrete was somewhat variable. Some areas were extremely porous, and the alkaline water from the warm spring seeped through, dripped on the penstocks, and destroyed the paint. An attempt to

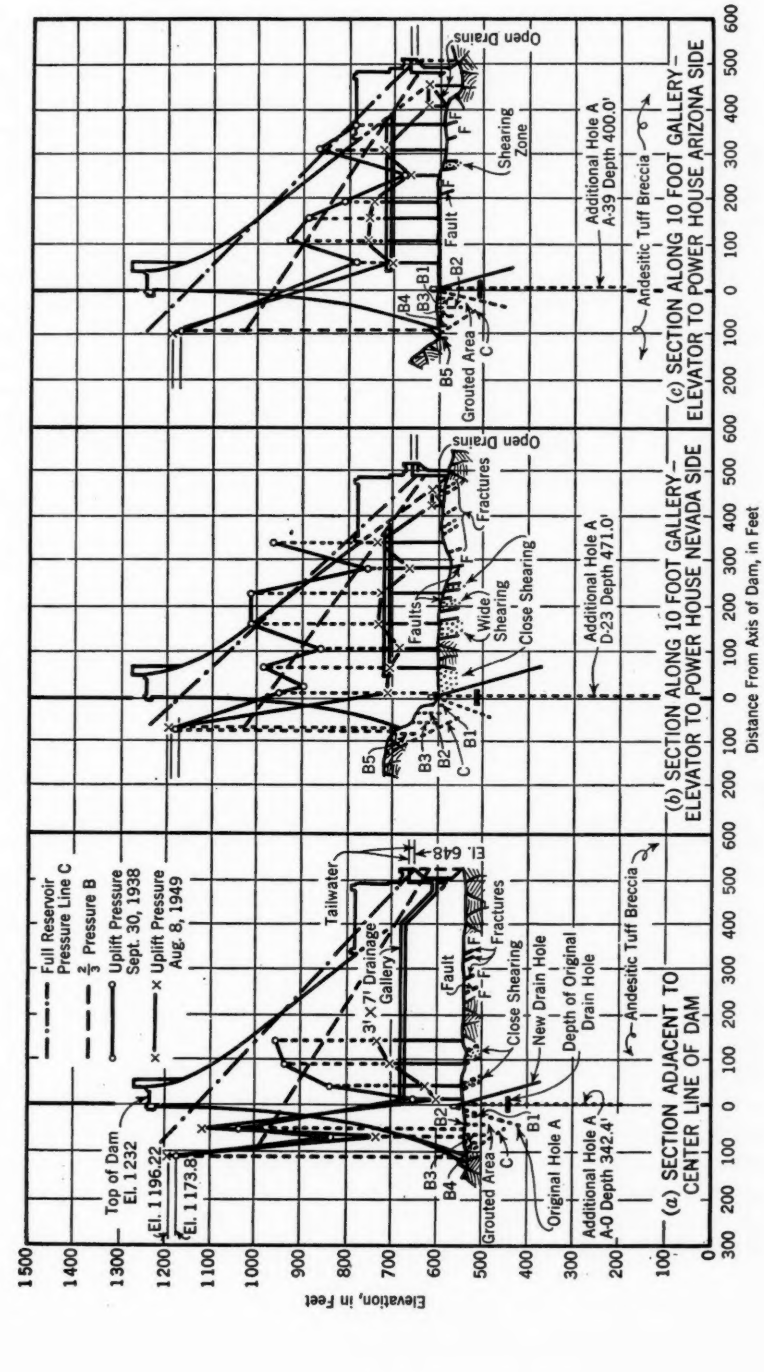

FIG. 6.—UPLIFT PRESSURE GRADIENTS

protect the paint had been made by installing metal troughs beneath the leaks and conveying the water to systems of pipe headers. However, during certain seasons of the year the humidity arising from the seepage water condensed and formed moisture on the metal, and the periods of wetting and drying caused deterioration of the paint and extensive corrosion as soon as the protective coating of paint had been penetrated. The expense involved in maintaining the outlet and penstock paint jobs was an item of considerable importance.

Increase in Uplift Pressure on Base of Dam.—The increasing uplift pressure on the base of the dam was of gravest concern to the engineers responsible for the safety of the structure. The measurements of uplift pressure were obtained from 4 lines of pipes installed for this purpose. There were 7 pipes along the Nevada bench, 6 pipes adjacent to the line of centers, 7 pipes along the Arizona bench, and 4 pipes in the upper circumferential drainage gallery. Semi-monthly measurements were started August 12, 1935, and continued until December 15, 1946. After that date they were made at monthly intervals. Uplift pressure measurements were also made at some drains from 1935 to 1937 to supplement the information obtained from the regular uplift pressure pipes.

In the design of Hoover Dam, the following assumptions relative to uplift pressure were used in making the stress analysis:

> "Uplift pressure intensities were assumed to vary as a straight line from full reservoir pressure at the upstream face to zero or tailwater pressure at the downstream face.
>
> "At planes of contact between the dam and canyon rock, uplift pressures were assumed to be effective over two-thirds the area."[2]

The maximum uplift pressures at the base of the dam just prior to the time that the additional grouting was started is shown in Figs. 6 and 7. The two-thirds full pressure line (B) and the full reservoir pressure line (C) are shown also in these figures. The worst condition of uplift pressure occurred along the Nevada abutment at line B, in which the magnitude of pressure exceeded that of the full reservoir pressure line (C). At the time of this measurement (September 30, 1938) the reservoir water surface was at El. 1178.8. It had been noted that the ratio of the uplift pressures to the reservoir pressures had been increasing after each annual rise in reservoir level, and it was considered essential to correct this undesirable condition.

Plans and Preparation for Corrective Measures.—The chief complication to any proposed remedial measure was the ungrouted abutment joints that had been provided for contact grouting between the concrete of the dam and rock abutments. Grouting these joints would effectively seal the areas in which grout had leaked when the A-hole grouting was in progress, but this grouting could not be done until after the dam had deflected downstream under water load. The results of precise surveys made in 1938 by triangulation indicated that the structure had deflected downstream about ½ in. As soon as this fact had been determined, the 2 abutment joints were grouted. This

[2] "Boulder Canyon Project," *Technical Investigations Bulletin 4*, Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo., Final Reports, Part V, p. 66.

resulted in stopping several noticeable leaks that appeared at the junction of the downstream face of the dam and the abutments and also stopped the serious seepage into the lower galleries of the Nevada wing of the powerhouse.

The increasing intensity of the uplift pressures near the downstream toe of the dam, particularly beneath the central section of the power plant, was considered to be the most serious situation that had developed. Plans were made to start the remedial measures while the abutment joint grouting was in progress. A line of drainage holes was to be drilled through the concrete

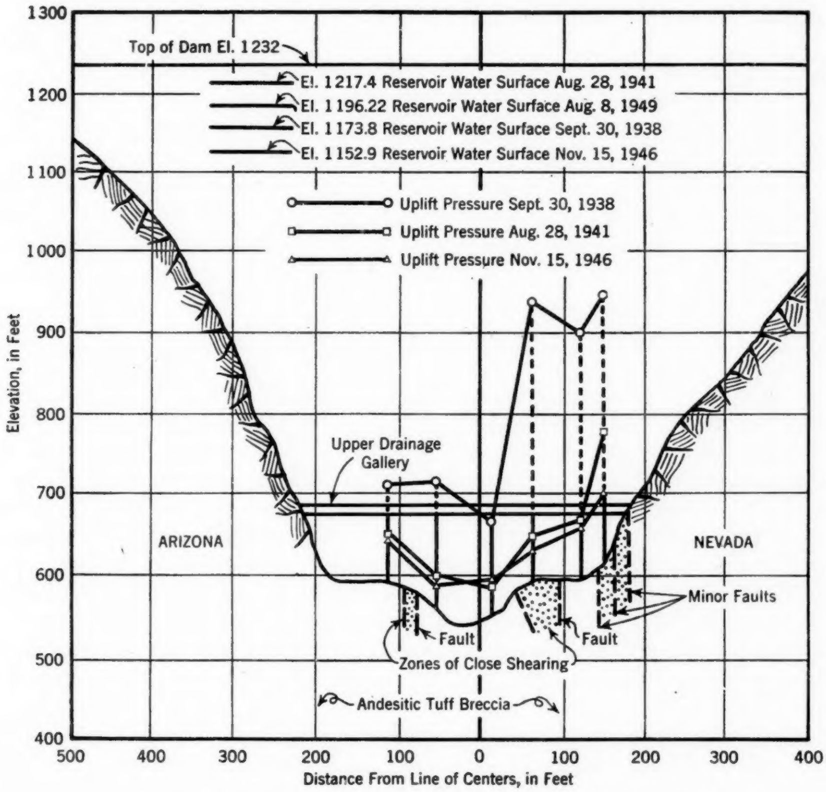

Fig. 7.—Uplift Pressure Gradient in Developed Section Along Center Line of Upper Drainage Gallery

of the dam into the foundation rock in the area of the high uplift pressure. Actually 2 rows of holes were drilled for this purpose, one row being vertical and the other dipping upstream at an angle of 45°. The holes were drilled from one of the lower galleries in the powerhouse (at El. 616) that would permit any intercepted flow to drain into the lowest sump by gravity. Several of these drains discharged large flows of warm water.

In attempting to plan an effective program for additional grouting, consideration was given to regrouting areas in the foundation in which grouting

had been abandoned before completion. Because of the increasing amount of seepage that was developing in widespread areas, the effectiveness of the original grouting was problematical, and it was realized that the available information on existing foundation conditions was inadequate. Therefore, a systematic exploration of the foundation was started by drilling BX-size core holes, in an attempt to find where defects in the foundation rock existed. Based on the results of the exploratory drilling, a plan was developed to form an additional grout curtain downstream from the row of A holes. The additional cutoff curtain was to extend deeper into the foundation than the original cutoff curtain.

Exploratory drilling revealed also that the original grout curtain extended an insufficient distance laterally into both abutments. The indications were that the area in the Nevada abutment between the dam and the spillway structure required consolidation by grouting. There was a particularly porous zone in the abutment on the reservoir side of the Nevada spillway.

As a result of this exploratory drilling it was planned to continue the new cutoff curtain into each abutment and to form a deeper curtain along the reservoir side of the Nevada spillway. After this grouting had been accomplished, it was further planned to drill additional drain holes downstream from the new grout curtain.

Method of Grouting and Material Used

At the start of the program of additional grouting, considerable experimentation was required to determine a suitable procedure that would not increase the uplift pressure on the base of the dam. The first holes drilled from the grout and drainage gallery at El. 553 developed flows of water that provided sufficient drainage in some cases to reduce the uplift pressure slightly. When grouting operations started, the uplift pressure would increase. Continual vigilance on the part of the engineers directing the grouting was required to keep a high uplift pressure from developing and yet accomplish an effective job of grouting. It was realized that single-stage grouting of a deep hole that crossed several water-bearing seams was not the most efficient practice, but this was done until a suitable method combining stage and packer grouting could be developed.

As soon as the grouting work became organized, a systematic procedure of stage grouting was used. In areas in which open seams were crossed (as determined by flow of water into the hole), it was customary to drill slightly beyond the seam and then grout. After allowing the grout to set for approximately 16 hours, the hardened grout was drilled from the hole. The condition of the grout determined the type of bit used in opening the hole and, whenever possible, borium sawtooth bits were used to save wear on the diamond bits.

In holes in which flows of water from 200 to 300 gal per min were encountered, experimental grouting with packers was tried. The first packers did not prove successful because of the difficulty in seating them against the flow of water in holes of nonuniform diameter. Stage grouting was resorted to, and the holes were grouted in successive stages by starting at the top of the hole and then working progressively downward. Later a satisfactory

packer and a method for inserting it against large flows of water was developed.[3]

Cement Used.—An entirely satisfactory cement, suitable for foundation grouting, had not been developed during the construction period at Hoover Dam. Standard portland cement had been used successfully in areas free from hot alkaline water, but when grouting in the warm spring areas this type cement was unsatisfactory. When it came in contact with the hot alkaline water, a flash set would occur and the grout pumps would stall as the pumping pressure built up without forcing any grout into the foundation. The high temperature was presumed to be a contributing cause of this trouble, consequently several attempts were made to cool the area surrounding the grout holes in the foundation by pumping cool water into the holes prior to grouging. This procedure was not successful, apparently because an insufficient amount of water had been pumped into the grout holes, and premature stiffening of cement continued to occur. The exact cause of this difficulty was not determined. However, the suspicion continued to be prevalant that either the temperature of the water or the contact of the cement with the alkaline salts—or possibly the cominbation of the two—might have been contributing factors to this trouble.

The first step in an attempt to obtain a satisfactory grouting cement was the use of an oil well-type grouting cement that had been found successful in grouting areas in which hot salt water had been encountered in oil fields. Unfortunately, these cements were ground fairly coarse compared with later practices in manufacturing standard and modified cements. The average specific surfaces ranged from 1,100 to 1,400 sq cm per gram for cements of this type manufactured in the west coast area. However, a special grind of oil well cement that was finer than usual was obtained. This cement had an average specific surface of 1,865 sq cm per gram or about the same as that of the standard portland cements obtainable.

The oil well cement had some very desirable characteristics for grouting, but it was not completely satisfactory. It contained a small percentage of the usual dark-colored particles of unground clinker that had a tendency to settle out from the rest of the grout when the thin mixes were pumped through long supply lines. This coarse material had always been undesirable for injecting into holes in tight ground.

While the field forces were occupied in the elimination of coarse material in the cement, laboratory investigations were being made to find a finely ground cement with the characteristics of oil well cement. It was found that by adding a commercial retarder, composed of calcium salt of lignin sulphonic acid and triethanolamine, to the modified cement a resulting product was obtained that had the desirable characteristics and was more finely ground than the oil well cement. This product was used in grouting throughout most of the foundation area in which warm water was encountered.

Grouting Program

Preliminary Work.—The first step in the grouting program was a check of the inspector's daily reports of the grouting activities of the construction period.

[3] "Header Assembly Permits Grouting Against High Hydrostatic Pressures," by George T. Evans, *Civil Engineering*, Vol. 19, June, 1949, p. 48.

The locations in which groups of grout had been abandoned indicated areas in which additional grouting appeared desirable. A group of 9 of the original Nevada A holes that penetrated the zone of minor faulting between El. 840 and El. 940 in the area bearing cold water were opened and redrilled to depths of 150 ft, and an attempt was made to regrout them. This grouting was not entirely satisfactory, since only small quantities of cement, ranging from 2 to 7 sacks per hole, could be injected. The seams in the rock surrounding these holes had been closed apparently by the original grouting, so it was felt that the additional grouting would be more effective if new holes were used.

Foundation Conditions Encountered.—While the grout crew was attempting to regrout the Nevada A holes between El. 840 and El. 940, unexpected developments were encountered by the drill crew working in the foundation gallery at El. 553. The original drainage plan that had been followed during construction between axis stations 5+46 and 8+04 was to drill alternate drain holes on 10-ft centers to maximum depths of 100 ft, as shown in Fig. 3. In order to relieve the high uplift pressure and explore the foundation area, intermediate holes were drilled along the row of drains. This drilling disclosed the presence of manganese seams extending across the foundation beneath the river channel at El. 525. Lenses of broken rock were found at lower elevations, and flows of water were encountered, indicating the presence of open cracks or seams.

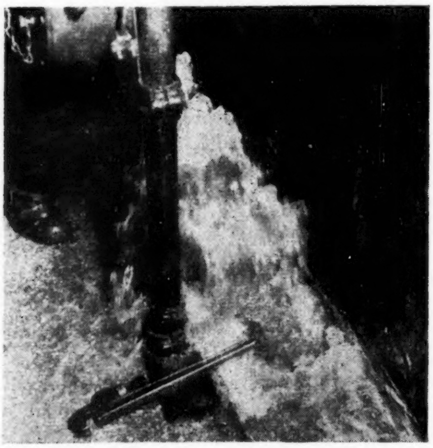

FIG. 8.—FLOW OF WATER FROM FOUNDATION GROUT HOLE

Steps were immediately taken to correct these defects in the foundation. It was decided to convert all of the original drain holes into a new line of A holes that would form an additional cutoff curtain, and later drill a new drainage system downstream from this second grout curtain. The procedure planned was to wash the soft manganese material from the seams in the foundation using the group of 3 holes at a time to prevent having too large an area of the foundation beneath the 726-ft high dam unsupported. Grouting with packers was tried in this area, but it was unsuccessful because of excessive interconnections between holes, through cracks and seams in the foundation rock.

As the drilling progressed, areas of broken rock shear zones, lenses of uncemented volcanic sand, and open seams that produced large flows of water, such as that shown in Fig. 8, were encountered. Each hole had individual characteristics, and every sack of cement injected benefited the foundation. The policy adopted was to drill the new grout holes deep enough to assure that one "run" of drilling (approximately the length of drilling necessary to fill a 5-ft core barrel) was in good sound rock. This was determined by examination of

the core from the hole. As the drilling was carried on with 3 shifts per day, different men were responsible for determining if the bottom of the hole was in good sound rock. This personal factor, together with the natural irregularities of the foundation conditions, resulted in considerable variation in the depth of holes in the new grout curtain.

The resulting grout curtain is shown in Fig. 9. The deepest hole was hole D-23 on the Nevada side of the river channel. This hole was one of the most important holes drilled. Its final depth was 479.8 ft, and 322 sacks of cement were used in grouting it. At a depth of 420 to 450 ft it penetrated a shear zone that was the apparent source of the uplift pressure over the greater part of the base of the dam. Although the quantity of cement used in grouting was not great, it had a widespread effect in reducing the uplift pressure. Over 5,000 sacks of cement were injected in this immediate area before the program was completed, and this resulted in a material reduction of the uplift pressure.

As the grouting progressed, it was found that fairly deep holes were necessary. The method of closures was adopted as the optimum method of procedure. In this method, the primary holes were drilled and grouted at fairly wide spacing. The next holes were drilled and grouted halfway between the primary holes and this procedure continued until the amount of grout used indicated that the foundation was tight. When unusual conditions indicated that additional holes were desirable, they were drilled as needed.

The Arizona abutment was grouted in a fairly uniform manner. The primary holes took the most grout, and subsequent holes required smaller quantities of grout as the abutment grew progressively tighter. The maximum quantity of cement injected in 1 hole in the Arizona abutment was 8,258 sacks in hole A-124 at El. 1000. Other holes that took large quantities of cement were as follows:

Hole	Sacks of cement	Hole	Sacks of cement
A–35	1,817	A–100	1,927
A–40	4,882	A–106	3,598
A–46	3,368	A–129	1,486
A–55	3,585	A–138	2,235

The grouting of the Nevada abutment was complicated by the presence of cracks in the andesitic geological formation. The first grouting in this area, completed during the construction period, indicated the presence of fairly extensive cracks between El. 800 and El. 1000. In exploring this area by core drilling, several cores, showing cracks up to 2 in. wide well filled with grout, were found. Although during the construction period over 13,000 sacks of cement had been injected in this area, during this period seepage appeared on the canyon wall above the roof and behind the Nevada wing of the powerhouse. Because of the unsightly appearance of this seepage, considerable effort was exerted to dry up the wet area above the roof. Although the quantity of grout injected in this area was fairly small, it was necessary to drill about 20 holes before the path of the seepage was intercepted.

Blanket Grouting of the Upstream End of the Nevada Penstock Tunnel.—During the construction of the lower Nevada penstock tunnel, a faulted zone

was encountered about 150 ft downstream from the tunnel plug. No major seams were crossed in this area. The disturbance consisted of a maze of smaller cracks that crossed the tunnel at an angle of about 45° with the axis, in plan. This area had been grouted during the construction period using both low-pressure and high-pressure methods. The low-pressure grouting was for the purpose of filling voids back of the lining caused by over-breakage of the abutment rock, and the high-pressure grouting sealed the rock around the tunnel bore and also formed 2 cutoff rings around the tunnel at the plug section.

The porous concrete through which the seepage entered the tunnel covered such an extensive area that it was decided to regrout the upper end of the tunnel for a distance of about 300 ft immediately downstream from the plug. This was done by laying out patterns of holes at intervals of 20 ft along the axis of the tunnel. Each pattern consisted of 7 holes, sloping upward, above the horizontal diameter of the tunnel. The patterns were laid out with the

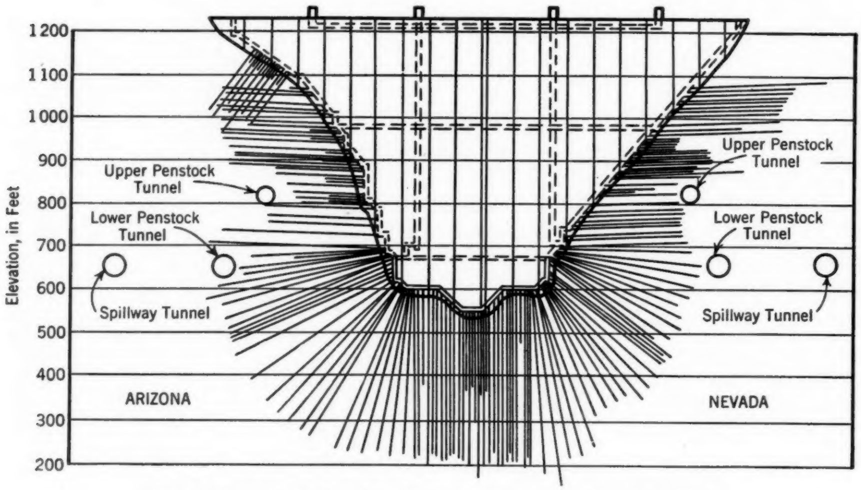

Fig. 9.—Profile of Dam Site Showing Additional Grout Curtain

intention of intersecting as many seams as possible; consequently the holes on the river side of the tunnel were drilled pointing upstream and the holes on the abutment side pointed downstream.

In drilling holes in this area, cracks that produced large flows of water were penetrated at considerable depth. In order to dry up the wet areas in the tunnel, it was necessary to drill holes ranging in depth from 100 to 250 ft. The most effective procedure was to drill the deep holes and grout in stages, using packers and fairly high pressures. A total of 142 holes was drilled to an aggregate depth of 17,767 ft, and the amount of cement used in grouting this area was 6,589 sacks.

As the program progressed, it became necessary to extend the grout curtain deeper into the Nevada abutment. Deep holes were drilled, first from the Nevada penstock tunnel and then from the spillway tunnel. When drilling to the right of the spillway tunnel, cracks were found that yielded great flows

of water, up to 450 gal per min from a BX-size hole. Fig. 10 illustrates the flow encountered in a hole that had been grouted in stages to a depth of 178 ft. This flow was encountered in drilling 14 ft further. Over 56,000 sacks of cement were used in grouting this area.

Before the grouting was completed in this area, core holes were drilled for test purposes and for additional exploration of the abutment. Films of grout as thick as $1\frac{3}{4}$ in. were found in the cracks in the water-bearing area. Only a small quantity of seepage was obtained from the holes drilled through the grouted areas after the grouting was completed, indicating that the grouting program had been effective.

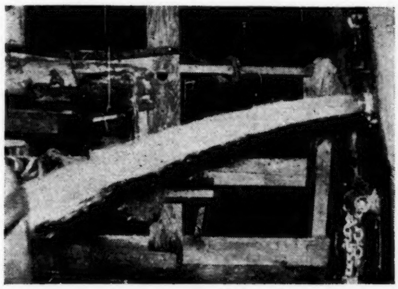

Fig. 10.—Flow From Exploratory Hole in Nevada Abutment

Curtain Grouting Along Reservoir Side of Nevada Spillway.—At the time the cutoff curtain grouting was being extended into the Nevada abutment, the spillway tunnel was unwatered in order to make some alterations at the downstream portal. This afforded an excellent opportunity for examination of the condition of the tunnel for seepage. Cold water appeared at various places along the tunnel, issuing from cracks in the lining, indicating that reservoir water was apparently passing underneath the Nevada spillway basin. Therefore, a cutoff curtain was established along the reservoir side of the spillway.

During the construction period the grouting activities in the area of the Nevada spillway had been complicated by the presence of a mud seam near the upstream end of the spillway weir. In accessible places the mud had been cleaned from the seam and a concrete cutoff wall had been placed across the seam; subsequently the area had been grouted beneath the overflow section of the spillway. The consolidation grouting consisted of three rows of holes 18 ft apart, the holes being spaced 20 ft on centers. The cutoff curtain consisted of a line of holes spaced 10 ft on centers, drilled along the reservoir side of the weir section to a maximum depth of 50 ft.

The additional cutoff curtain was placed along the upstream edge of the spillway section. At the time this grouting was done, the reservoir water covered most of the area. A casing was cemented into shallow holes in the foundation rock and all drilling and grouting was performed through the casing. Detection of underwater grout leaks from the surface of the foundation rock was made by using a water scope, and leaks of this type were effectively sealed by manipulating the grout mix.

The additional cutoff curtain consisted of holes drilled approximately 10 ft on centers as shown in Fig. 11. The holes were drilled in a fan-shaped pattern at the upstream end of the spillway structure in order to extend the grout curtain into the abutment and were approximately vertical throughout the length of the structure. At the downstream end, the holes were inclined in a

downstream direction to connect with the main grout curtain of the dam between the penstock and spillway tunnels.

Drainage Program

As previously described, the first additional drains were drilled through the downstream toe of the dam from the gallery at El. 616 in the central section of the powerhouse, to relieve the uplift pressure acting over the downstream area of the base. As soon as this drilling had been effected, additional holes and grouting were organized in a systematic procedure. The work of drilling drainage holes was alternated with the drilling of grout holes in order to provide continuous employment for the drill crews.

New Drains Drilled From the Foundation Gallery.—As soon as all the additional grouting in a group of 6 or more holes of the new cutoff curtain beneath the dam had been completed by utilizing holes that were

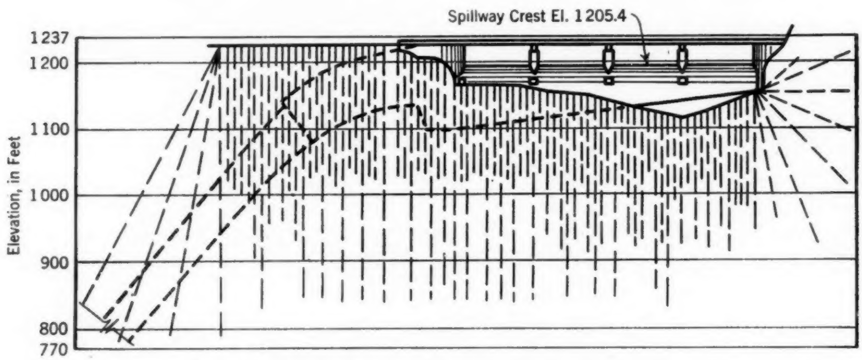

Fig. 11.—Nevada Spillway—Additional Grout Curtain

originally drains, drilling of the new drains in that area was started. These holes were arranged as shown in Fig. 12 and were drilled to maximum depths of 250 ft. The general plan was to drill these holes pointing downstream at an angle of 15° with the plane of the axis of the dam, and these new drains were drilled EX size.

At the beginning of the drainage program, the new drains were drilled to depths that produced a notable effect in the uplift pressure gages. By experimentation it was found that in the original river gorge, holes 170 ft deep drilled on 5-ft centers were effective. A spacing of 10 ft on centers was used across both benches at El. 600, and the holes were drilled slightly deeper in areas in which core drilling indicated defective rock.

The vertical shafts in which the spiral stairways were located were not designed to accommodate a diamond drill rig. Although the stair treads could be uncoupled and swung to one side to provide access to the gutter in which the drains were located, the center post did not afford sufficient clearance for setting up a diamond drill in the shaft. Additional drains, therefore, were not drilled from the shafts, but patterns of drain holes were laid out from the inclined stairways above and below the shafts to serve the abutment area,

and the holes were drilled from locations in which there was sufficient working space.

Additional drains were drilled in both abutments, downstream from the areas served by the curtain grouting. The drilling was done from the construction adits that extended from the Nevada wing of the power plant to the

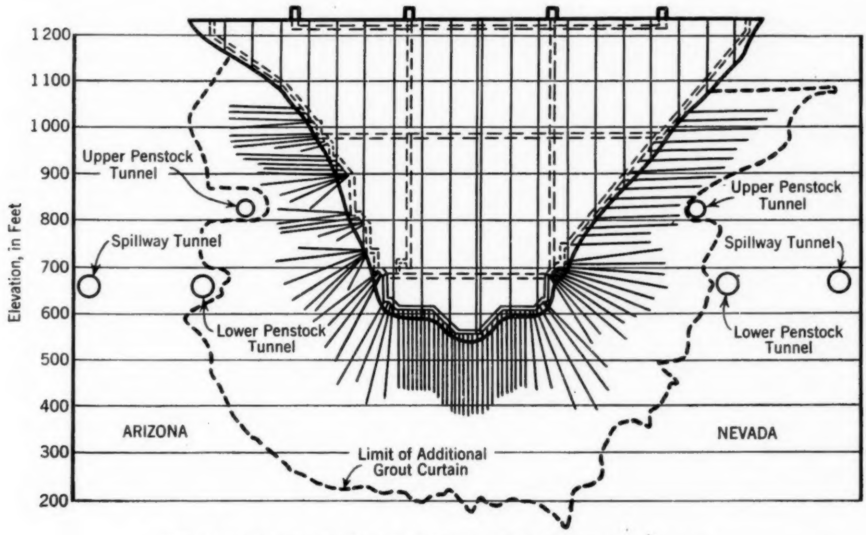

FIG. 12.—PROFILE OF DAM SITE SHOWING NEW DRAINAGE SYSTEM

Nevada spillway tunnel and from the Arizona wing of the power plant to the Arizona penstock tunnel. These drains picked up small flows of seepage that had passed the grout curtain and were effective in drying up wet areas on the canyon walls behind the back walls of the wing sections of the power plant.

RESULTS OF PROGRAM OF ADDITIONAL GROUTING AND DRAINAGE

Reduction in Uplift Pressure.—One of the most significant results of the program of additional grouting and drainage was the lowering of the uplift pressure on the base of the dam to considerably less than that used in the assumptions on which the design was based. Curves showing the uplift pressure before the work started in the fall of 1938 and the pressure that occurred during the high water period of 1949 are shown in Figs. 6 and 7. The pressure observed at set A along the line of centers of the dam is now considerably less than one half the magnitude of the pressure that occurred during the fall of 1938. The observed pressure at set B along the gallery at El. 705 on the Nevada side of the dam is about one third of the magnitude of the pressure that occurred during the fall of 1938. At set C, along the El. 705 gallery on the Arizona side of the dam, the observed pressure is now about one half that observed in 1938. The only zone beneath the base of the dam in which the uplift pressure may be greater than the two-thirds pressure line (B) is upstream from the grout curtain, an area in which there is no provision for

measuring uplift pressures. The uplift pressure at the downstream toe of the dam beneath the central section of the powerhouse has been reduced until it is no longer of any concern.

Reduction in Discharge from Drains and Seepage Water.—During the season of 1938, prior to starting the additional grouting, the seepage water entering the galleries from the foundation drainage system was in excess of 200 gal per min. Shortly after this program had been started, when a number of deep drains had been drilled to relieve the uplift pressure and very little grouting had been done, flows from the drains increased to over 2,000 gal per min. As the grouting progressed, the discharge from the drains decreased until it is now (1950) about 135 gal per min.

Prior to the grouting program, seepage water found its way into some of the construction grouting galleries that were not equipped with drainage systems. As the seepage water accumulated, it was customary to dip up this water in buckets and carry it out by hand. In 1935, a maximum of 95 buckets of water per week was removed from the galleries. As a result of the drying up of the abutments due to grouting, this seepage entering the galleries has been eliminated.

The drainage water from the abutment area that could be measured was that which entered the penstock tunnels. The bulk of the seepage found its way into the lower Nevada penstock tunnel and a nominal volume of seepage entered the other tunnels. Before the grouting program was started, 3 pumps with a total capacity of 3,300 gal per min were used for pumping the seepage from the lower Nevada penstock tunnel, and weir measurements indicated that a maximum of 2,660 gal per min was pumped. This flow was reduced until the entire volume could be handled by a small eductor and the pumps were removed from the tunnel.

Reduction in Maintenance Costs.—Prior to the additional grouting and drainage program, an item of major concern and expense was the protection of the penstocks and other metal work in the tunnels from the corrosive effect of the excessive seepage entering through the construction joints and porous concrete in the arches of the tunnels. This condition was especially bad in the lower Nevada and lower Arizona penstock tunnels. During the years 1939 and 1940 the services of from 4 to 5 pipe fitters with helpers were normally required to install and maintain metal troughs and other protective devices in the arches of the penstock tunnels. As the program progressed, less work was required; by 1946, the labor requirement had diminished until the work could be accomplished by the part time services of 1 pipe fitter and helper, and at present this work is no longer necessary. Repainting the penstocks to protect the metal cost $29,979.18 in 1939, but by 1946 the requirement for painting was only $5,894.16. The cost of pumping the seepage water from the tunnels amounted to $11,270.34 in 1939, but by 1946 this item was $5,861.68, and since 1946 there has been a further reduction in maintenance costs.

Cost of Grouting and Drainage Program

The entire program of foundation treatment at Hoover Dam extended over a period of years in which a wide variation of costs occurred. The work

was started in the pre-World War II period and extended through the duration of the war and into the post-war period. In order to make a fair comparison of the cost of this work, Table 1 was prepared to show the cost of foundation grouting and drainage of masonry dams constructed during the period from 1931 to 1947. The dates of the last cost reported used in compiling these data are included to show the approximate time that the work was completed.

In Table 1 the cost of the grouting and drainage is expressed in a percentage of the total cost of the structures only, and the cost of the respective appurtenant works of these dams is not considered. In general the cost of foundation treatment ranges between 1% and 2%. In the case of the Owyhee Dam, an extensive program of grouting was necessary because of structural defects in the foundation. For this reason, the cost of the foundation grouting and drainage amounted to 4.97% of the cost of the dam. Marshall Ford Dam was built in two stages, each of which required grouting and drainage. The

TABLE 1.—Cost in Dollars of Foundation Grouting and Drainage of Concrete Dams Constructed by the USBR, 1927–1947

Dam	State	Total cost of dam	Volume of concrete (cu yd)	Foundation Grouting and Drainage		Date of cost report
				Cost	Percentage of total cost	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Gibson	Mont.	2,388,000	161,173	29,000	1.21	April, 1931
Deadwood	Idaho	1,359,000	55,463	13,000	0.96	June, 1931
Owyhee	Ore.	6,728,000	488,113	334,000	4.97	May, 1938
Seminoe	Wyo.	7,083,000	173,127	138,000	1.95	Aug., 1941
Parker	Ariz.-Calif.	4,695,000	290,640	48,000	1.03	Nov., 1942
Grand Coulee	Wash.	112,990,000	10,181,742	1,460,000	1.29	Dec., 1942
Marshall Ford	Tex.	23,395,000	1,838,167	572,000	2.46	May, 1947
Shasta	Calif.	74,567,000	6,353,227	676,000	0.91	May, 1947
Hoover	Ariz.-Nev.	77,549,000	3,251,137	1,840,000	2.38	July, 1947
Friant	Calif.	18,636,000	2,030,736	267,000	1.43	Dec., 1947

result of this two-fold treatment was to bring the cost of grouting and drainage to 2.46%. The cost of the foundation grouting and drainage program at Hoover Dam amounted to $1,840,000, or only 2.37% of the cost of the dam.

Summary and Conclusions

The original plan for the foundation treatment at Hoover Dam by grouting and drainage, based on the satisfactory foundation treatment of 50 of the highest dams in service at that time, was not sufficient for the structure because of the exceedingly high pressure developed after the reservoir filled. The inadequacy of the treatment was indicated by seepage into the tunnels, seepage through the abutments, and excessive uplift pressure on the base of the dam. Geological defects in the andesitic formation comprising the foundation and abutments complicated these undesirable conditions and made additional treatment necessary.

To prevent seepage and to reduce uplift pressure, the depth of the grout curtain beneath the maximum section of the dam should have been about

300 ft (equivalent to 41% of the height of the dam) instead of the 21% used in the original design.

To render effective aid in controlling the uplift pressure on the base of the dam, the depth of the drain holes beneath the maximum section should have been about 200 ft (equivalent to 28% of the height of the dam) instead of the 14% used in the design.

To correct geological defects in the foundation and abutments, a program of washing and grouting inadequate areas was necessary. This part of the program was based on conditions uncovered by exploratory drilling.

For effective grouting, it was found that a combination of stage (or successive) grouting, combined with packer grouting was the most effective. For packer grouting, drill holes from $1\frac{1}{2}$ in. to 2 in. in diameter were necessary. The spacing of the holes varied with conditions encountered, but in general the spacing ranged from 5 to 20 ft measured along the foundation gallery.

The grouting procedure required the use of extremely thin grout mixtures and pressures as high as could be safely maintained without displacing the foundation rock. In general, the grout mixture used in the final grouting was thinner and the pressures somewhat lower than those used in the original grouting. The water cement ratio of the grout mixture used in the original program ranged from 7:1, measured by volume, for tight holes to 1:1 for holes in which leaks developed. The maximum pressures used were generally about 750 lb per sq in., although in a few holes pressures as high as 1,000 lb per sq in. were used. In the program of final treatment, the water-to-cement ratios usually ranged from 15:1 to 5:1, although in areas of tight rock the initial injections of grout occasionally consisted of 20:1 mixtures. Grout mixtures of these consistencies were generally pumped with pressures ranging from 550 to 600 lb per sq in. The use of a commercial retarder for the grout mixtures was advantageous in areas of hot alkaline water.

At the conclusion of the program of final foundation treatment, it was evident that by means of a judicious program of grouting and drainage, the seepage through the abutments can be practically eliminated, and the uplift pressure on the base of the dam can be controlled adequately and be maintained at a value materially less than that used in the design assumptions.